Quest for Optimum Coding and Modulation Schemes for EME

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Ten years of fascination with amateur radio in the 1950s and early 1960s led me to a professional life in basic research and university teaching. Over the next forty years, my research in radio astronomy taught me a great deal about extracting extremely weak signals from noise, and analyzing their content. In 2001, back on the air as an active radio amateur, I began thinking about ways to apply techniques learned and developed in the research world to the problems of weak-signal communication on our VHF and UHF bands.

My presentation in Florence will review some basics of communication theory, a complex field in which I have much interest but no professional expertise. I will then describe the motivation, rationale, and performance trade-offs leading to the digital communication modes implemented in my software programs WSJT, MAP65, and WSPR, with particular emphasis on the most recent developments and the modes suitable for EME. My quest for the optimum ways to exchange messages with high reliability, despite having very weak signals, has been a fascinating learning experience involving much study and many experiments. By no means have all of my ideas been successful! — but all have been fun, as well as instructive.

Most attendees at this conference are already familiar with the JT65 protocol, which was designed especially for VHF EME. In this summary paper I assume such familiarity and describe two relatively new projects: the MAP65 software and a new experimental mode called WSPR.

MAP65

MAP65 is a computer program designed as the back end of a wideband polarization-matching receiver for JT65 signals. It works together with the Linrad[1] software written by SM5BSZ, and takes advantage of RF and IF hardware providing signal channels for two orthogonal polarizations. As an example, my current 144 MHz station uses dual-polarization yagis and matched baseband converters. I configure Linrad to use a four-channel, 24-bit soundcard to sample I and Q baseband signals for each polarization at a 96 kHz rate. After Linrad's superb wideband noise blanking has been applied, the digitized signals are passed to MAP65 in the form of UDP packets. MAP65 automatically finds all detectable JT65 signals in a 90 kHz passband, matches the linear polarization angle of each one, decodes their messages, and provides the operator with a "band map" displaying callsigns, operating frequencies, polarization angles, and messages received over the past 20 minutes or so. The program provides a companion transmitting facility, and it runs under either Windows or Linux. With my available hardware I choose to run Linrad under Linux and MAP65 under Windows, but any combination is possible — including running both programs in a single computer.

[1] Linrad Home Page: www.nitehawk.com/sm5bsz/linuxdsp/linrad.htm

MAP65 uses the JT65 protocol[2] popularized in the program WSJT[3]. JT65 was designed to enable EME contacts between moderate-sized amateur VHF/UHF stations. Its high efficiency is a result of using time-synchronized transmissions, compact structured messages, strong forward error correction, and 65-tone frequency shift keying. The most important difference between MAP65 and WSJT (when the latter is running in JT65B mode) is that WSJT receives a single 2 – 4 kHz bandwidth and decodes one signal at a time. In contrast, MAP65 works with dual-polarization antennas and accepts a full 90 kHz bandwidth. MAP65 scans the entire received passband, automatically determining the frequency, drift rate, time offset, and polarization state of every detectable JT65 signal, and decoding each one.

I have been testing various versions of MAP65 on the air since May 2007, and have used it to make more than 600 EME QSOs on 144 MHz. I find it a pleasure to use. It's very exciting to have the whole 144 MHz digital EME sub-band (say, 144.070 – 144.160) available on one's computer screen simultaneously, including panoramic spectral displays and the text of all messages being sent and received. If the moon is up, and especially if it has not yet set in Europe, I generally see ten to twenty EME signals on my screen at any given time. The signals may originate anywhere in the world where the moon is above the horizon, and the program decodes them all. When a new station shows up and calls CQ, I see his signal and callsign immediately and can respond after his first transmission. No advance knowledge, schedules or internet liaison is required.

A screen shot of MAP65 is shown in Figure 1. This snapshot was taken after MAP65 had processed data recorded between 0745 and 0800 UTC on November 11, 2006, during the second weekend of the 2006 ARRL EME contest. (Odd-numbered minutes from 0747 to 0753 UTC are absent from the recording because I was transmitting then, working WA8CLT on 144.131.) If you were "on the moon" at this time using JT65B on 2 meters, your signal is probably among those found and decoded by MAP65. My EME antenna in 2006 was very modest: a pair of 3λ cross-polarized yagis stacked side by side, a few feet above the roof of my house.

Figure 1 shows four active MAP65 windows:

1. The main window, similar to that of WSJT, used for conducting QSOs.
2. A "Waterfall" window with separate panels presenting a wideband spectral view and a zoomed-in region around the selected QSO frequency.
3. A scrolling "Messages" window listing the results of all transmissions decoded over a specified time interval, typically 10–20 minutes.
4. A "Band Map" window presenting a summary listing by frequency of all stations decoded in the specified time interval.

Many additional details of the MAP65 program and its capabilities are contained in a paper presented at Microwave Update 2007 and published in the proceedings[4] of that conference. MAP65 was used by several stations, including my own, during the 2007 ARRL EME contest, and was found to be highly effective for contest use.

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[2] J. Taylor, K1JT, "The JT65 Communications Protocol", *QEX*, September-October 2005, pp. 3–12.
[3] This paper assumes some basic familiarity with WSJT. If you need more background, the WSJT Home Page can be found at physics.princeton.edu/pulsar/K1JT/.
[4] J. Taylor, K1JT, "MAP65: A Panoramic, Polarization-Matching Receiver for JT65," http://physics.princeton.edu/pulsar/K1JT/MAP65.pdf

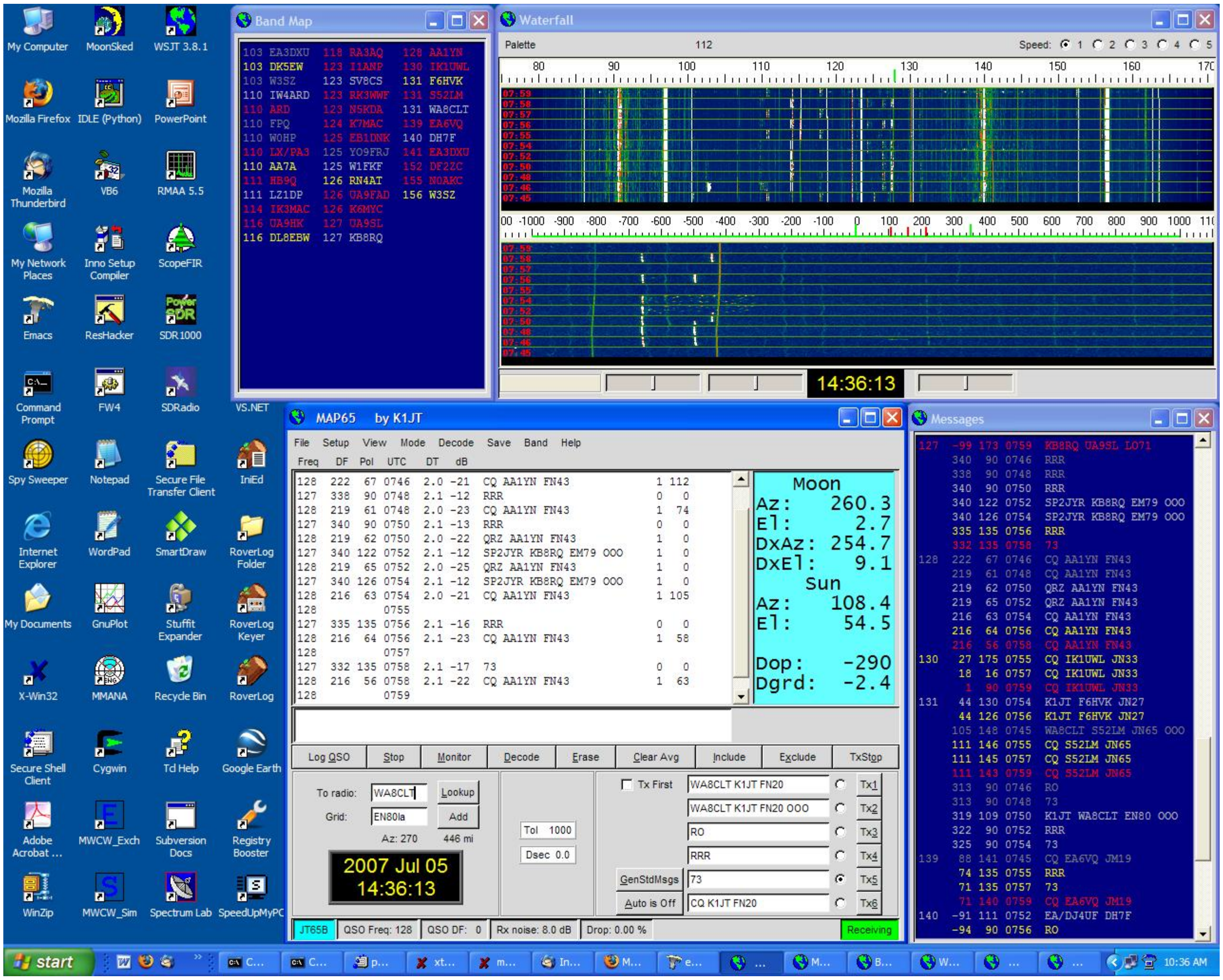

Figure 1. MAP65 screen shot after receiving 11 minutes of wideband data recorded during the 2006 ARRL EME contest at 144 MHz.

WSPR

WSPR mode was created in March 2008. The name is pronounced "whisper," which seems appropriate for a mode designed for extremely weak signals; it is an acronym for "Weak Signal Propagation Reporter," and has come to be used for both the protocol and a computer program that implements it. The protocol was developed for beacon-like signals originating from QRP transmitters on the LF, MF, and HF bands, but also with advance thinking toward its possible use for VHF EME QSOs. WSPR uses structured messages with a high degree of compression, strong forward error correction, an embedded sync vector for establishing accurate time and frequency offsets between transmitter and receiver, and 4-tone frequency shift keying at 1.46 baud. Transmissions last for slightly less than 2 minutes. Total signal bandwidth is about 6 Hz, so WSPR signals are about 1/60 the bandwidth of JT65B signals and 1/4 the bandwidth of 20 wpm CW. Many WSPR signals can fit into a few hundred Hz of spectrum, with few collisions. Figure 2 presents a screen shot of WSPR in use on the 30 m band.

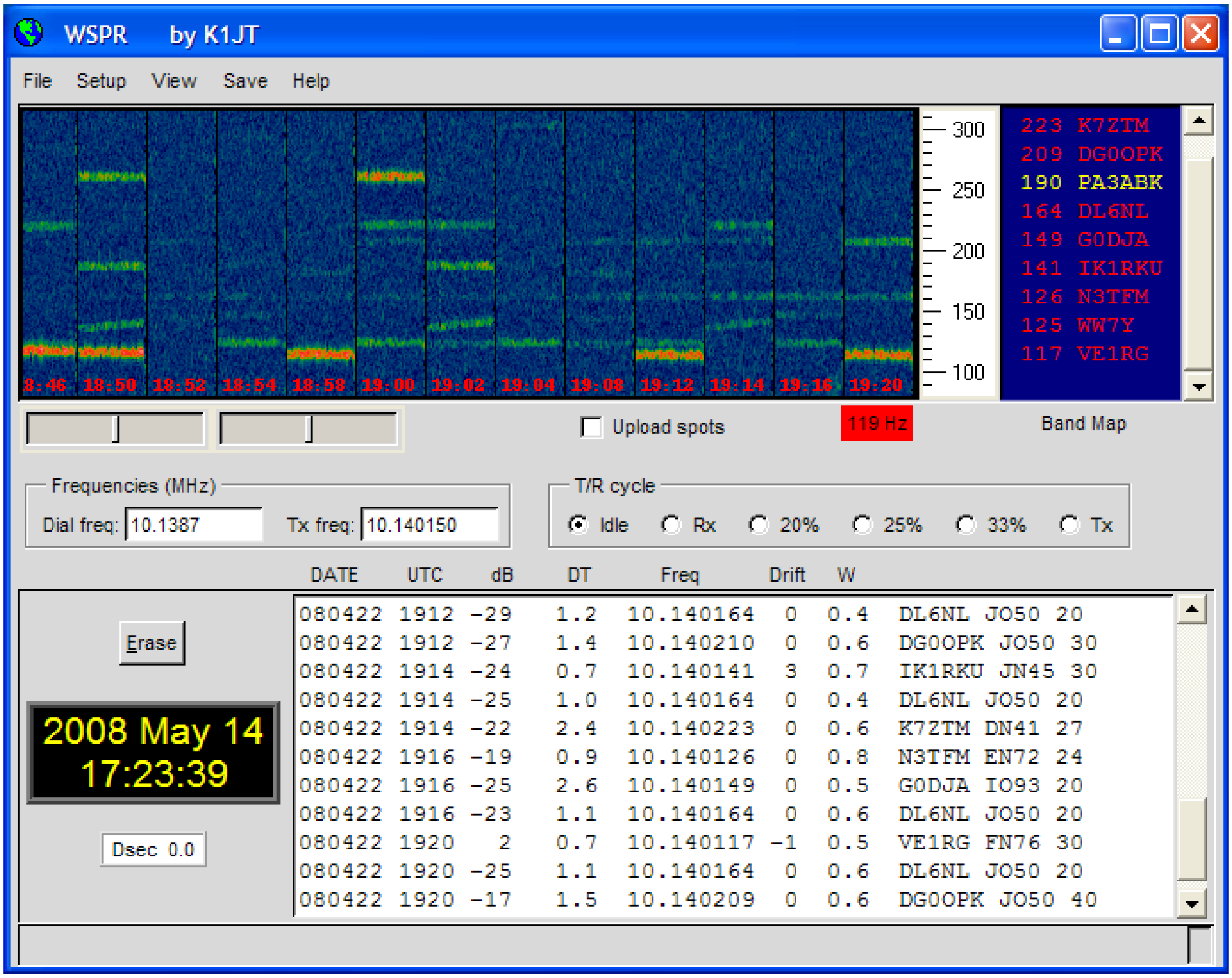

Figure 2. Screen shot showing many WSPR-mode signals received on 30 m, in a bandwidth of 200 Hz.

Over the past two months WSPR had been actively used by some four hundred operators around the world, mostly using QRP and QRPP power levels on the HF bands. Successful tests have also been made at 508 kHz and on the VHF bands. In its original mode of operation (which was not intended for making 2-way QSOs) the program transmits during a specified fraction of available 2-minute slots, and receives in the rest. A typical “transmitting percentage” is 25%. Messages consist of callsign, grid locator, and transmitter power in dBm; on the HF bands, most operators have been using power levels of 100 mW to 1 W. As you can see in Figure 2, WSPR signals can be decoded with signal-to-noise ratios as low as –29 dB in the standard reference bandwidth of 2500 Hz. As in JT65, strong forward error correction guarantees that messages are almost always received exactly as transmitted, or not at all.

Figure 3 is a screen shot showing signals from the first test of WSPR on an EME path. The signal was provided by VK7MO and received at K1JT. Rex has a modest 4 x 10 element array, and for this test he ran just 150 Watts.

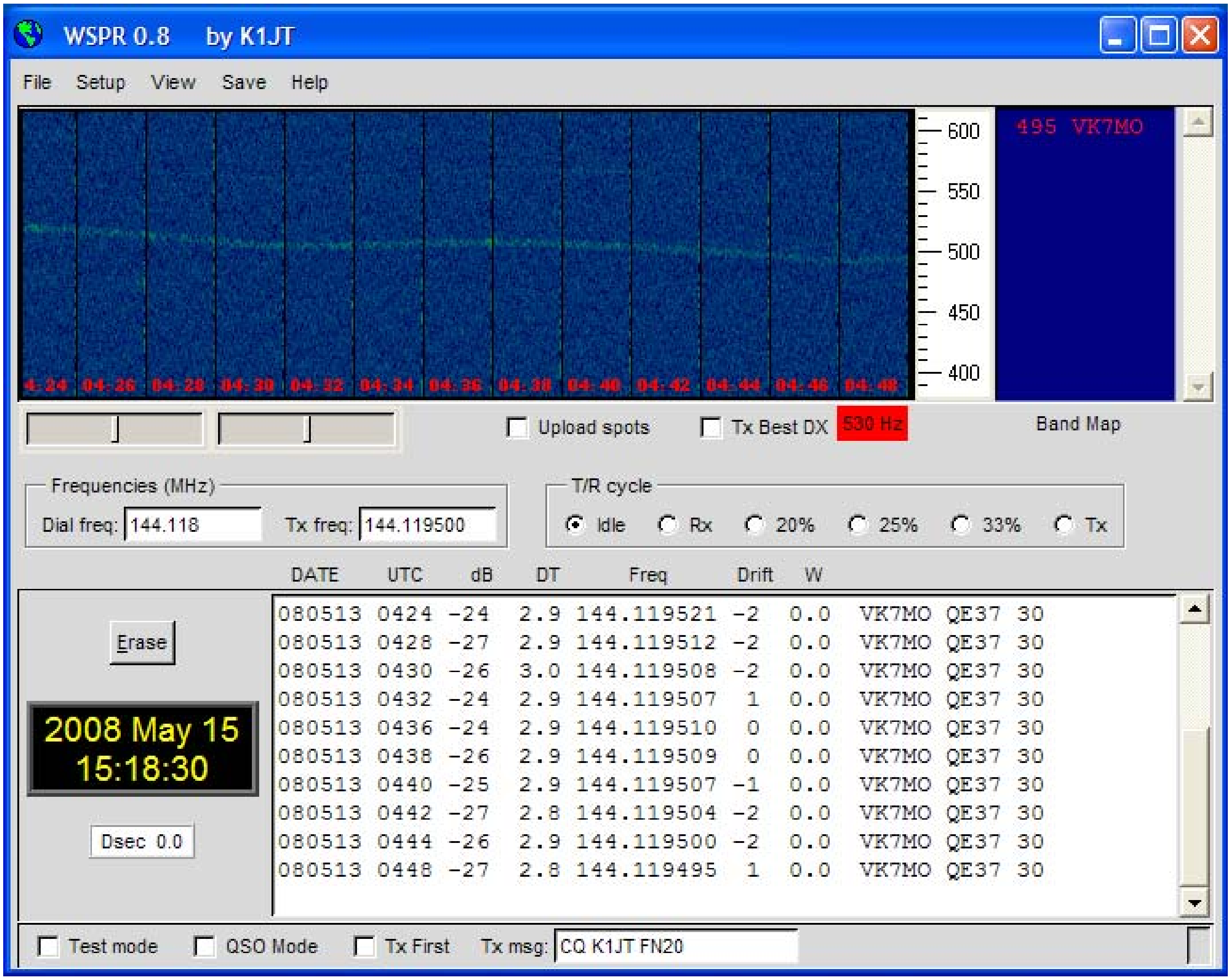

Figure 3. Screen shot showing the WSPR signal of VK7MO being received at K1JT via 144 MHz EME.

In addition to its beacon-like messages, the WSPR protocol offers a rich variety of message types useful for 2-way contacts. Their formats are illustrated by the templates and examples presented in Table 1. This list is still being developed as I write; more complete information will be available at the time of the conference in Florence.

Upper-case letters and numerals are conveyed in the WSPR protocol exactly as shown in the templates. Lower-case items are replaced by appropriate variable information, for example `call=K1JT`, `grid=FN20`, `rpt=S1` to `S9`, `name=VICTORIA`, `wx=SNOW`, `freetext=CUL JACK`, and so on, as shown in the examples.

Table 1. Templates and examples of WSPR messages.

Template	Example of usage
CQ call grid	CQ K1JT FN20
CQ p/call	CQ PJ4/K1JT
<call1> call2	<K1JT> W6CQZ
DE call grid	DE W6CQZ CM87
DE p/call	DE PJ4/K1JT
call1 <call2> rpt	W6CQZ <K1JT> S4
QRZ call	QRZ K1JT
p/call rpt	PJ4/W6CQZ S4
call1 <call2> R rpt	K1JT <W6CQZ> R S3
p/call R rpt	PJ4/K1JT R S3
<call1> call2 RRR	<W6CQZ> K1JT RRR
call1 <call2> RRR	W6CQZ <K1JT> RRR
DE p/call RRR	DE PJ4/K1JT RRR
73 DE call grid	73 DE W6CQZ CM87
73 DE p/call	73 DE PJ4/K1JT
TNX name 73 GL	TNX VICTORIA 73 GL
OP name 73 GL	OP HARRY 73 GL
pwr W DIPOLE	5 W DIPOLE
pwr W VERTICAL	10 W VERTICAL
pwr W gain DBD	1 W 0 DBD
pwr W gain DBD 73 GL	1500 W 21 DBD 73 GL
PSE QSY freq KHZ	PSE QSY 1811 KHZ
WX wx temp F/C wind	WX SNOW -5 C CALM
freetext	CUL JACK

WSPR messages may contain one full callsign and one "hash-coded" callsign. The transmission of hash codes is indicated by angle brackets surrounding the call, as in <K1JT>; the brackets appear in displays of both transmitted and received messages. Since hashing is a many-to-one mapping, the process is not reversible. However, if a full callsign has been decoded in a previous transmission, the decoder may assume that matching hash codes usually imply matching callsigns. With a 15-bit hash code, the chances of misidentification are small, especially within the confines of a particular QSO.

A minimal QSO using WSPR mode might look like the following sequence of messages:

```
1.  CQ K1JT FN20
2.                      <K1JT> W6CQZ
3.  W6CQZ <K1JT> S4
4.                      K1JT <W6CQZ> R S3
5.  <W6CQZ> K1JT RRR
6.                      TNX JOE 73 GL
```

A third-party operator listening to this QSO from the beginning would copy everything just as the participating stations do. Even if only one of the QSO partners can be copied at the third station, both callsigns will be received in full. If the third-party operator tunes into the middle of a QSO, so that his decoder cannot yet identify one of the hashed callsigns, it will produce something like

```
W6CQZ <...> S4
```

instead of the full message. He must then stay tuned to determine the identity of the missing callsign. There will be no ambiguities at all for the QSO partners themselves. Full callsigns are always decoded (or already available, in the case of one's own call) before their hash codes are needed.

Signal report S1 corresponds to –30 dB on the WSJT scale, S2 = –27 dB, S3 = –24 dB, etc., up to S9 = –6 dB. On this scale, the threshold for signal audibility is around S5 to S6. The placeholder "p/" stands for an add-on prefix or suffix in compound callsigns like ZB2/DF2ZC or DH7FB/P. Information conveying the prefix or suffix replaces the information that would otherwise carry a grid locator or hashed callsign. Some extended-length callsigns like VK3ABCD are accommodated in a similar way.

Items in Table 1 like "pwr", "gain", "temp", and "freq" stand for numbers. A 2m EME station might send the message

```
1500 W 21 DBD
```

to inform his QSO partner about his equipment. Similarly, a QRP HF station might send

```
1 W 0 DBD
```

or

```
5 W DIPOLE
```

If an operator finishes a QSO on 80 m and wants to try 160 m next, he might send

```
PSE QSY 1811 KHZ
```

Weather reports can be conveyed by setting "wx" to SUNNY, CLOUDY, RAIN, or SNOW; "temp" can be transmitted in degrees C or F, with appropriate conversions made automatically at the receiving end; "wind" can be set to CALM, BREEZES, or WINDY. Names may contain up to nine letters, and "freetext" may contain any combination of eight or fewer letters, numerals, spaces, and the punctuation marks + . / ? . Space has been reserved in the WSPR protocol for many more "canned" or "partly canned" messages like those in the final group of templates. I hereby solicit suggestions for additional messages to be included in this group. Note that the variable information to be inserted in a partly-canned message should be no more than one, two, or possibly three numbers or words.

Regular users of JT65 will be interested in a more detailed comparison of the JT65 and WSPR protocols. Table 2 presents such a comparison; in this table the specified JT65 bandwidth is that for sub-mode JT65B.

Table 2. Basic specifications for the JT65 and WSPR protocols.

	JT65	WSPR
Message length (bits)	72	50
Forward error correction	RS (63,12)	Convolutional, K=32, r=1/2
Channel symbols	126	162
Sync vector (bits)	126	162
Modulation	65-FSK	4-FSK
Keying rate (baud)	2.69	1.46
Transmission length (s)	46.8	110.6
Occupied bandwidth (Hz)	355	5.9

The first WSPR-mode QSO was made just one week ago as I write, using a special version of the WSPR program. However, future software evolution will most likely follow a different path. It seems best to keep the WSPR program relatively simple and intended for the purpose of automatic, beacon-like transmission and reception of propagation test signals. The next released version of WSPR will, however, be able to decode the QSO-mode messages as well as the beacon-like signals. For QSO purposes the WSPR protocol will be absorbed into a future version of WSJT. This seems desirable and efficient because WSJT already has the necessary tools for setting up messages, controlling transmit/receive sequences, and the like.

How does WSPR compare in sensitivity with other weak signal communication modes? Under the assumption of additive white Gaussian noise, no QSB, and Doppler spreading less than 1 Hz, the numbers given in Table 3 will apply. (It should be noted that JT65 uses 1-minute T/R sequences while WSPR uses 2-minute sequences, and that averaging of multiple WSPR transmissions has not yet been tested.) In general, I believe that WSPR will be effective over any propagation path that provides S/N exceeding –29 dB in reference bandwidth 2500 Hz, with Doppler spreading less than about 1 Hz. Such paths should include most LF, MF, and HF paths of interest to amateurs, as well as the EME path at VHF. At the time of writing, EME tests of WSPR have been made only on 144 MHz, where it works well. I do not expect WSPR to be effective (in its present form) at 432 MHz and higher, because of too much Doppler broadening.

Table 3. Approximate sensitivity comparisons for CW, JT65B, and WSPR.

	Threshold S/N (dB)
CW (best human operators)	–18
JT65B (KV decoder)	–24
JT65B (Average of 3 transmissions, KV decoder)	–27
JT65B (Deep search)	–28
WSPR	–29
WSPR (Average of 3 transmissions)	–32

For those with technical interest in the WSPR protocol, here are a few additional details. The

WSPR message payload is 50 bits of information in every transmission. Most message formats use 28 bits for a standard callsign and 15 bits for a hash-coded callsign or grid locator. The remaining 7 bits convey signal reports, acknowledgments, power levels, and special message types. Special messages can use the first 43 bits for any dedicated purpose. The WSPR protocol uses continuous-phase 4-tone FSK with tone spacing and keying rate equal to 12000/8192 = 1.46 Hz. Each transmission contains (50+K-1) × 2 = 162 channel symbols, and each symbol conveys both a data bit (MSB) and a synchronizing bit (LSB). Transmissions last for 162*8192/12000 = 110.6 s.

The WSJT, MAP65, and WSPR programs are available for free download on the WSJT Home Page, `physics.princeton.edu/pulsar/K1JT/.` These programs are all open-source, licensed under the Gnu General Public License. Contributions to the programs by other interested amateurs are encouraged. Source code for the programs is maintained in an open repository at `developer.berlios.de/projects/wsjt/.`